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Historical Values of Water and Carbon Intensity of Global Electricity Production

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Abstract. The global production of electricity is reliant upon the availability of water resources for the cooling of thermoelectric power plants and in the production of hydroelectricity. Additionally, much of the current global electricity production requires the combustion of fossil fuels, which emit greenhouse gases and create a carbon footprint of electricity production. In this study, we investigate the historical values of global electricity production through country and regional accounting and comparison of carbon and water footprints from 1990–2018. Here we show water footprints of electricity production rising 1.6% year over year from 143 km^3 1990 to 220 km^3 in 2018. Additionally, the carbon footprint of electricity production increased 2.2% each year with nearly 14 $\times 10^{12}$ kg CO_{2e} emitted in 2018. Our analysis highlights regional comparisons of carbon emissions versus water intensity for a sustainable electricity transition across the globe, recommending the need to account for both resources in policy and technological decisions.

Keywords: Energy-Water Nexus; Electricity; Water Footprint; Carbon Footprint

1. Introduction

Achieving a globally sustainable energy system is a critical component in battling and mitigating climate change. A sustainable energy system requires not only the consideration of greenhouse gas emissions, but also water demands. Indeed, the interdependency between energy and water, termed the energy-water nexus, has been critical in the development of large-scale power plants across the globe [1]. Given their interdependence, it is unsurprising that there is consensus in the research community for the need to jointly manage water and energy resources. However, in practice, strategies and policies to manage these resources are often isolated from one another [2, 3]. The most widely recognized contributing factor for the lack of joint management is a dearth of data [4–6].

In this research, we specifically focus on the electricity-water nexus—the water demands for the operational production of electricity. The water demands of any given electricity system are highly variable and are influenced most notably by power plant characteristics such as fuel and cooling system type [7]. A large portion of previous work focuses on the water demands of thermoelectric power generation [7]. However, from an operational water footprint perspective, the largest water footprint for electricity can be attributed to hydroelectricity—a low carbon electricity source [8]. However, there are many challenges with associating a water footprint for hydroelectricity, most notably due to the multi-use nature of our reservoirs [9–11].

Previous research has highlighted the global impacts of energy-for-water [12, 13] and global water impacts from electricity production [8] and trade [14, 15]. Additionally, there have been several regional or country-specific studies that address the changes in water demands of electricity. For example, in Spain, water consumption for thermoelectric power plants is expected to increase over 25% from 2005-2030 [16]. In the United States, Peer and Sanders [17] determined that, while the water consumption intensity (volume per unit electricity) has remained relatively consistent, increased electricity demand has created larger water demands. However, there have been no studies that systematically catalog these changes in water consumption intensity for countries across the globe. In addition, previous research identified notable tradeoffs in balancing the water demands of electricity with greenhouse gas emissions [18–22]. Therefore, in this study, we juxtapose the changing water and carbon intensities of electricity for each country to compare trends in carbon and water footprints.

Understanding these changes in water and carbon intensity of electricity is essential in planning for the impacts of a changing climate. Several studies have highlighted the effect of climate change on the water availability for thermoelectric power plants. A study in the United States found that climate change negatively impacts the production capacity of 99% of power plants [23]. Additionally, a significant decrease in power plant capacity in Europe and United States (6.3-19% and 4.4-16%, respectively) is predicted as a result of lower streamflows and higher river water temperatures due to climate change [24]. Thermoelectric power plants not only consume water resources but are also a source of thermal pollution in the water bodies to which they discharge. For example, the Rhine River basin in Europe was cited as the most thermally polluted watershed in the world [25]. Additional studies on thermal pollution have investigated downstream impacts of thermoelectric power plants [26], impacts on ecosystem health [27, 28], and overall water pollution level using the concept of grey water footprints [29]. In this manuscript, we focus on the consumptive (blue) water footprint of the electricity sector.

In addition to climate considerations, the power sector is transitioning due to economic, environmental, and public opinion pressures [17]. There is evidence that for every megawatt-hour of electricity switched from coal to natural gas approximately

1 m^3 of water consumption is avoided [30], with a savings of 200 million m^3 of water per year from switching in the State of Texas, alone [31]. Similarly, Wilson and Staffell [32] discuss the rapid carbon saving opportunities of switching from coal to natural gas with a carbon tax, yielding a global decrease of 3% of electricity-related emissions.

With energy system transitions and development, there are concerns for enhancing and improving energy security around the globe. The security, emissions intensity, and water intensity of an energy system are often in conflict with one another [16]. A prime example of the tradeoffs between environmental and energy security concerns is in the Mekong River basin [33], where dry years could increase the carbon footprint of electricity by as much as 20%. Chowdhury et al. [34] further discuss the changing carbon emissions of the Mekong River Basin associated with drought in an electricity grid dominated by hydroelectric generation.

In this analysis, we build upon previous assessments of the global water demands of electricity [e.g., 8] and describe the changes in water and carbon intensity for electricity from 1990–2018 at the country and regional scale, utilizing existing, publicly available data from the International Energy Agency (IEA) and literature estimates. Here, we only consider the operational water and carbon footprint of electricity, ignoring the fuel supply chain [35] and water consumed in the processing and building of power generation facilities, including wind turbines [36] or photovoltaic solar panels. All data are published in an online repository [37] and are made available to advance an understanding of trends in the global energy-water nexus. Our work emphasizes the need for joint consideration of water intensity and carbon emissions in global electricity transitions, highlighting country, regional, and continental trends.

2. Methods

One of the most challenging aspects of conducting global assessments on the energy-water nexus is a lack of location-specific data. Therefore, in order to establish estimates at the country-scale, we must accept some degree of uncertainty. This section details the development and analysis of country-level (m^3/MWh) water intensities and carbon intensities (kg CO_{2e}/MWh) for electricity across the globe and their changes across the last three decades.

2.1. Electricity Generation and Carbon Emissions

Annual country-level electricity profiles and carbon emissions from electricity and heat were collected from the IEA between 1990 and 2018, the latest year with complete data at the time of writing [38]. The data were accessed from the IEA's API. The data include electricity generation by source from 1990 to 2018 for a majority of countries. The IEA database does not provide data for every country in the world; our complete database includes 145 countries in total. Countries with incomplete or missing electricity profiles are removed from this analysis. For countries with complete electricity profiles, but incomplete or missing carbon profiles, carbon footprints are calculated using electricity generation values and average US emissions intensities for the year 2018 (in kg/MWh) for coal, oil, and natural gas from the US Environmental Protection Agency Emissions & Generation Resource Integrated Database (eGRID) [39]. When applicable, the average carbon intensity for oil was used for biomass, waste, and "other" generation categories. All code and data for this study are made available in a separate repository [37].

2.2. Water and Carbon Footprints

The volume of water consumed for electricity is a direct result of technological (in the case of thermal power plants) and climatic (in the case of hydroelectric power plants) factors [1]. There are many empirical estimations of water consumption for thermal power generation, most of which are focused on the US [e.g., 40–42]. There are comparatively fewer estimations of water consumption for hydroelectricity given the dependence on local climate [e.g., 8, 10].

In this study, given the lack of country-specific data, we apply fractional estimates of cooling technologies [43], D, for regions, r, fuel type, f, and cooling type, c, to fuel-based generation values, $G_{i,f}$. These factors are applied in each country, i, in a given region r (as defined by Davies et al. [43]) to estimate the amount of wet-cooled generation in each country, $G_{i,f,c}$ (Equation 1). These estimates are further used to isolate only fresh water cooled generation and estimate the fraction of open looped versus closed loop cooled generation.

$$G_{i,f,c} = G_{i,f} \times D_{r,f,c} \tag{1}$$

We use technology-specific estimations of water consumption for thermoelectric generation from Macknick et al. [40] and country-scale estimations of hydroelectric water footprints from Mekonnen et al. [8], $WC_{f,c}$, to calculate the water footprint for electricity for each country, WF_i (Equation 2). As previously noted, it is difficult to allocate the water footprint of hydropower across multi-purpose reservoirs. As a result, Mekonnen et al. [8] fully or partially allocated the footprint across the different uses of the reservoir. Additionally, Mekonnen et al. [8] relied upon an aggregation of a multitude of data sources for their calculation; for more information, their supporting information provides information on the sources and methodology.

$$WF_i = \sum_{f,c} G_{i,f,c} \times WC_{f,c} \tag{2}$$

For this study, we consider only the operational water consumption of electricity technologies. As such, the water intensities for solar photovoltaic and wind systems are considered to be zero. We also exclude the water consumption for fuel extraction and, in the case of biofuels, fuel generation. The exclusion of the water footprint of biofuels significantly reduces the water footprint of biofuel-generated electricity; however, this assumption was necessary for consistency across all fuel types.

Carbon footprints for each country are directly available from the IEA, determined using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 2 - Energy) [44, 45]. However there is no separation between the electricity sector and the heat sector in the publicly available IEA data. Therefore the carbon footprints presented here include the heat sector, which results in an overestimation of the total carbon footprint for electricity. The overestimation of carbon footprints on the country and regional scale would be most pronounced for areas with large, fossil-rich heating sectors.

2.3. Regional Aggregation and Resultant Database

Aggregations for regional and continental water and carbon footprints are based on UN regions [46] and continents as defined by the IEA. It is important to note that this database does not contain information for every country and therefore regional aggregations should be considered with care. The regional aggregations follow continental patterns. In the results figures, regions on a continent follow a similar color palette, and regional colors are consistent across all figures.

A complete dataset, including countries with partial data, can be found in the accompanying online database [37]. The database includes relevant code, raw data, and resultant data needed to recreate the entirety of the study.

3. Results and Discussion

Overall, the global water consumption for electricity generation (including hydroelectric generation) increased approximately 1.6% year over year from 143 km^3 in 1990 to 220 km^3 in 2018; see Figure 1 broken down by UN region [46]. Excluding electricity generated from hydroelectric dams, the total volume of consumed water for electricity is significantly lower at 12.0 km^3 in 1990, increasing to 23.8 km^3 in 2018. However, the water footprint of electricity excluding hydropower is increasing at a faster rate (2.5% each year). Spang et al. [41] estimated a consumption of 13 km^3 for non-hydro electricity production in 2008 compared to our estimate of 19.3 km^3. Global emissions, similarly, increased at a rate of 2.2% per year from 7.6 to 13.9 gigatonnes (10^{12} kg) CO_{2e}. Unsurprisingly, emissions and non-hydro water consumption show similar trends over time as they are both driven primarily by fossil fueled thermoelectric generation. These changes, however, are heterogeneous across the globe (Figure 1). To illustrate the overall impacts of global trends of electricity demand, we investigate the country-, regional-, and continental-scale trends of water and carbon footprints. These different spatial scales provide insight on the trends of different metrics within the energy-water nexus.

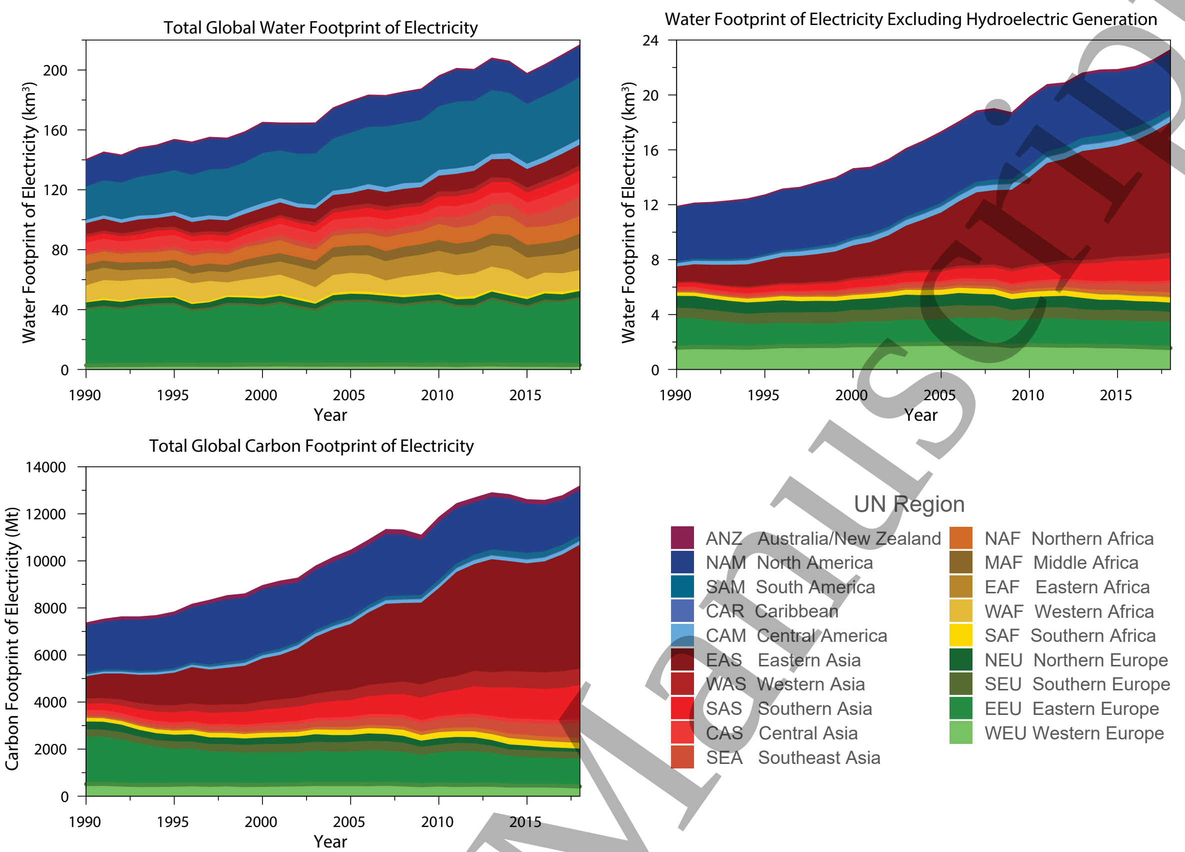

Figure 1. Water and carbon footprints of the global electricity sector have increased since 1990 with much of the increase occurring in developing regions such as Eastern Asia.

3.1. Country-level carbon and water footprints are increasing

In this study, we calculated the water and carbon footprints, including intensity normalized by megawatt hour (MWh), for each country from 1990 to 2018. These data are published in their entirety as an open access database via Zenodo [37], and they show the spatial variations in water and carbon footprints of countries around the globe. We developed simple linear regression models to assess trends in total carbon and water footprints as a function of time. Using a 90% confidence interval, Figure 2 indicates positive and negative trends in total (top) water and (bottom) carbon footprints over time.

Since 1990, there are very few countries that have reduced or maintained their water footprint over time. Japan shows a statistically significant (though relatively small) reduction in water footprint, while several European countries have no significant trend in either direction for water footprints. Conversely, several countries in Europe, including Russia, have experienced reductions in their total carbon footprint. These reductions are largely due to shifts in generation fuels from coal to natural gas as the latter becomes more accessible. In general, countries in South America, Northern Africa, and South Asia experience significantly positive trends in both total carbon

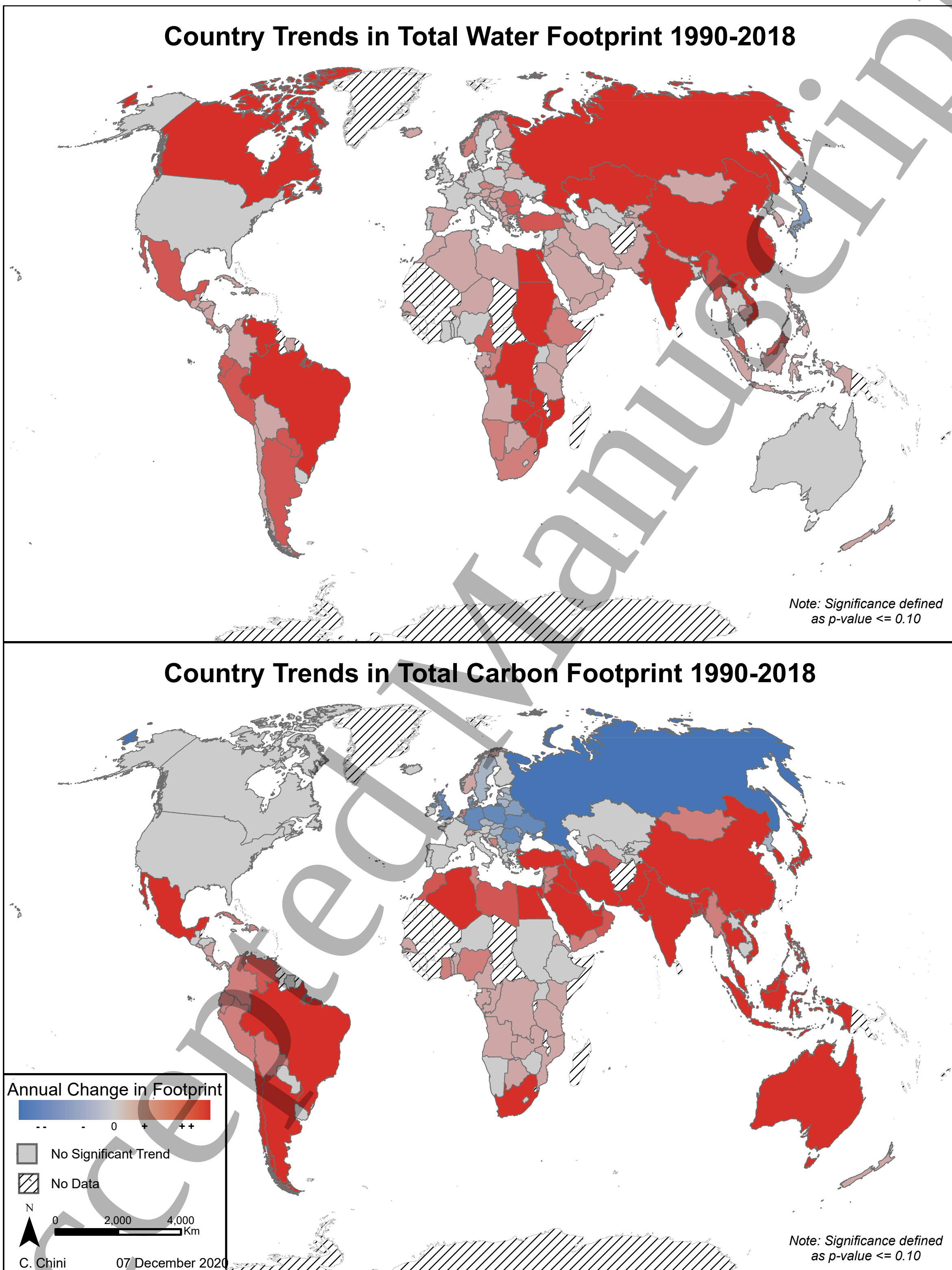

Figure 2. Simple linear regression models of total environmental footprint as a function of time illustrate the differing regional- and country-level trends. Japan is the only country with a consistently negative trend in total water footprint, while much of Europe exhibits a negative trend for carbon footprints. Southeast Asia, particularly due to China, has a strong positive trend for both carbon and water footprints

and water footprints due to increases in fossil fuel combustion for electricity generation. With respect to countries showing minimal or no statistically significant changes, only trends across the 29 years of data are illustrated—not accounting for more recent energy transitions. Additionally, the magnitude of these changes for both carbon and water footprints varies drastically across countries. It is concerning that a large number of countries are trending in a positive direction for total water and, especially, carbon footprints. While recent power plant construction in the United States has factored in water resources into decision-making through dry-cooling or water re-use [17, 47], it is clear that best management practices for reducing carbon and water footprints are not globally adapted. Figure S1 in the supporting information illustrates a selection of countries and their footprint trends for the past three decades. Carbon and water footprint data for each country are available for download [37].

These positive trends for carbon footprints in each country need to drastically reverse to meet climate goals set forth by international agencies. To meet the goals of the Paris Agreement, intensive reductions in carbon intensity of electricity are necessary, with accelerated expansion of renewable energy technologies required in the next decades [48]. Significant investment in the electricity and energy sectors are needed to support these reductions [49]. Finally, while some countries are trending towards zero-carbon technologies–specifically European countries, only half of the EU member states are expected to meet their greenhouse gas emissions targets [50], intensifying the need for broader electricity transitions.

In the United States, Grubert [51] discusses the relatively small amount of stranded fossil fuel plant years (15%) with a complete transition by 2035. Due to the relatively small remaining service life, it is feasible that the United States could economically transition away from fossil fuels in the next two or three decades. However, current carbon intensity levels in North America fall well short of a completely decarbonized electricity grid (about 400 kg CO_{2e}/MWh). The European Union has a goal of reducing emissions to at least 55% below 1990 levels by 2030 with a completely carbon neutral electricity mix by 2050 [52]. Currently, within the European continent, we estimate that only an 18% reduction in carbon footprint has occurred in the electricity sector. Similarly, China recently targeted 2060 for a carbon neutral energy sector [53]. This goal would be a significant reversal of its current historical trend, which shows consistent increases in the carbon footprint of electricity of approximately 160 $\times 10^9$ kg CO_{2e} per year since 1990.

From a water perspective, many of these countries, namely in Africa and Asia, currently face water scarcity [54], which is expected to be exacerbated with climate change. Increasing water footprints for electricity generation creates competition with other needs such as drinking water, food production, or other industrial/commercial uses [55]. While global water consumption for electricity generation remains a relatively small portion of the total water footprint of humanity (2%, including rainwater consumption for agriculture) [56], localized impacts such as thermal pollution from once-through cooling systems [27, 28] and ecological impacts from increased hydroelectric generation remain [57].

3.2. Regional carbon and water footprint relationships show marked carbon reduction priorities for developed areas

Using regional aggregations, Figures 3 and 4 illustrate the changing water and carbon intensities over time. A majority of the regions across the world had a decreasing water intensity of electricity production (Figure 3). However, total water footprint changes were offset by increasing electricity demands. More developed regions, such as those in Europe and North America, had minimal changes in electricity production or water intensity over time. Several regions, particularly those in Asia and Africa, show large increases in electricity production (by an order of magnitude), while simultaneously decreasing their electric water intensity. Only one region, Southern Africa (SAF), experienced both significant increases in electricity production and water intensity over time.

When comparing carbon intensities with electricity production, we see very different patterns. European regions, the Caribbean, and North America show steep declines in carbon intensity from 1990 to 2018. Conversely, due to their reliance on accessible fossil fuel generation, many developing regions such as those in Africa or Asia, show increases in electricity production coupled with somewhat static or slightly increasing carbon intensities.

These differing trends are further visualized on Figure 4. For example, it is clear that Europe and North America have worked to reduce their carbon intensity without imposing larger per unit electricity burdens on water supplies. Western Asia also shows negative trends in both resource intensities. Two regions, Western and Middle Africa (clustered at the bottom-right corner of Figure 4), experienced increases in the carbon intensity of electricity while reducing their water intensity. These tradeoffs are due to a historical electricity portfolio dominated by hydroelectric power—a high water, low carbon intensive energy source. When these regions began to expand their electricity generation over the past decades, carbon intensive fossil fuels increased carbon intensity while lowering the aggregated water intensity of the region.

The juxtaposition of these two resource intensities plotted against each other over time (Figure 4) further exposes the challenges of the sustainable energy transition. In certain regions, it is clearly evident that energy transitions are tackling both of these environmental concerns. However, in other locations—including developing regions—increased energy demands are not being met with sustainable strategies that seek to minimize the local (water) and global (carbon) impacts of electricity production. While decarbonization of the electricity sector gains a lot of international attention in reaching goals of the Paris Climate Agreement, the potential impact on water resources, with respect to the energy-water nexus, should not be ignored. Indeed, droughts in Europe and the United States reduce electricity generation capacity [24, 58], which in turn can lead to increased carbon intensity of electricity [33].

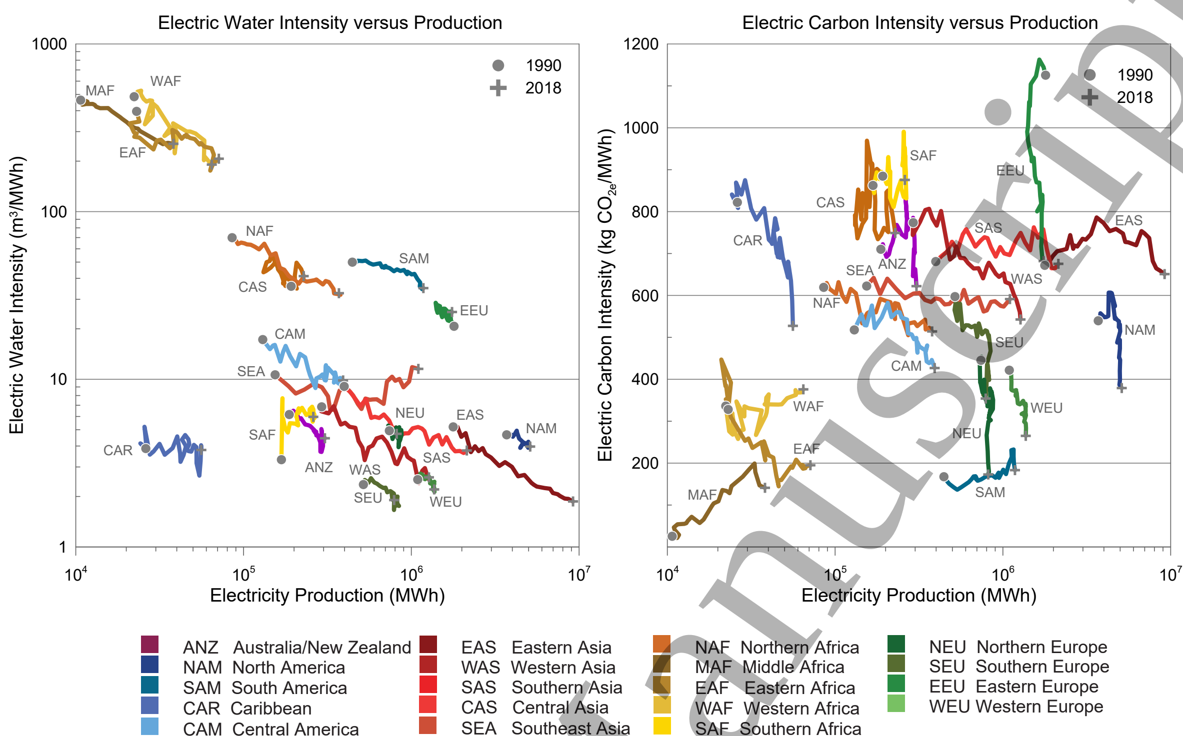

Figure 3. A majority of regions have an increasing electricity demand over time, with varying trends between water and carbon intensities. Each region is represented by a separate color. The horizontal axis is electricity production of each region and the vertical axes are water intensity (left) and carbon intensity (right). A circle represents the initial year of analysis, 1990, with a cross signifying the year 2018.

3.3. Continental scale carbon and water footprints highlight the ongoing role of coal in global electricity

In this section, we discuss the overall continental trends and contributions to global water and carbon footprints of electricity. Figure 5 illustrates the total water footprint, the water footprint excluding hydroelectricity, and total carbon footprint of generated electricity for five continental regions. We group North and South America into a single region and include Russia as part of Europe. While the water footprint of electricity has largely been increasing across the globe, the water footprint of Africa, Asia, and the Americas is increasing much more rapidly than that of Europe or Oceania. However, excluding hydroelectricity, Asia is the only continent seeing a marked increase in water footprint with slight decreases in total consumed water in the Americas and Europe. In contrast to the total water footprint, both the Americas and Europe show a negative trend in total carbon footprint. This trend for the Americas starts around 2005 (consistent with the timeline of increasing electricity generation from natural gas and a decrease in coal generation in the United States), but Europe shows a consistent decline since 1990. Asia, on the other hand, has a very steep increase in total carbon footprint, consistent with the accompanying growth in non-hydro electricity footprints–especially due to increasing electricity generation from coal in China and India.

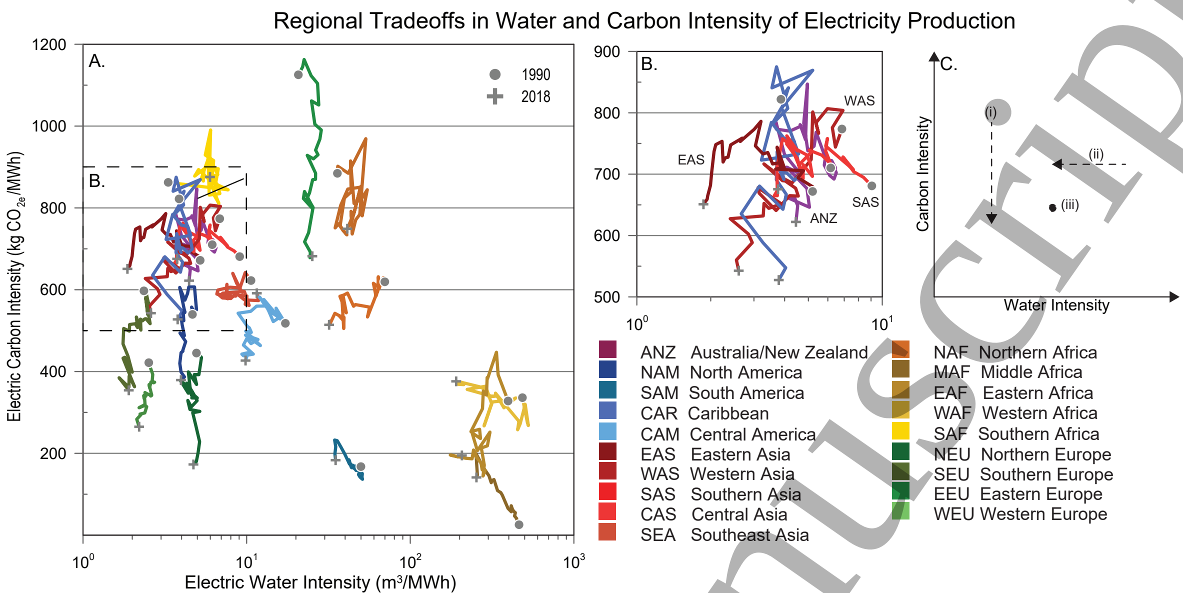

Figure 4. Trends of environmental impacts of electricity generation vary based on regions (A). Panel B shows a zoomed view of the cluster of regions on Panel A. There are three major regional characteristics which are shown in Panel C: (i) static water intensity with decreasing carbon intensity (e.g., near vertical line), (ii) decreasing water intensity with relatively static carbon intensity, and (iii) minimal changes in either intensity (e.g. clustering of points with no distinct trend). Each region is represented by a separate color. A circle represents the initial year of analysis, 1990, with a cross signifying the year 2018.

From 1990 to 2018, the global population increased by 2.2 billion people from 5.3 to 7.6 billion people [59]. The Americas, Europe, and Oceania accounted for only 323 million (14%) of this growth with the remaining population growth occurring in Asia and Africa. Additionally, the percentage of people with access to electricity across the globe has increased dramatically in this time (23.5% in 2005 to nearly 99% in 2018) according the the World Development Indicators from the World Bank [60]. Table 1 contextualizes the population growth with water and carbon footprints, illustrating the growing per capita water and carbon footprint in Asia (7 to 11 m^3/MWh and 600 to 2000 kg CO_{2e}/MWh). Interestingly, both Europe and the Americas increased their water footprint of electricity per capita while, simultaneously, decreasing their per capita carbon footprint. Comparatively, the continents with lower population growth had larger carbon footprints, by far, than Africa and Asia. These decoupled trends of carbon and water footprints illustrate the opportunities for both carbon and water management within the context of global electricity transitions.

4. Limitations

Similar to many other water for energy studies, there is uncertainty arising from the use of empirical water use intensities and further uncertainty from the lack of regional-

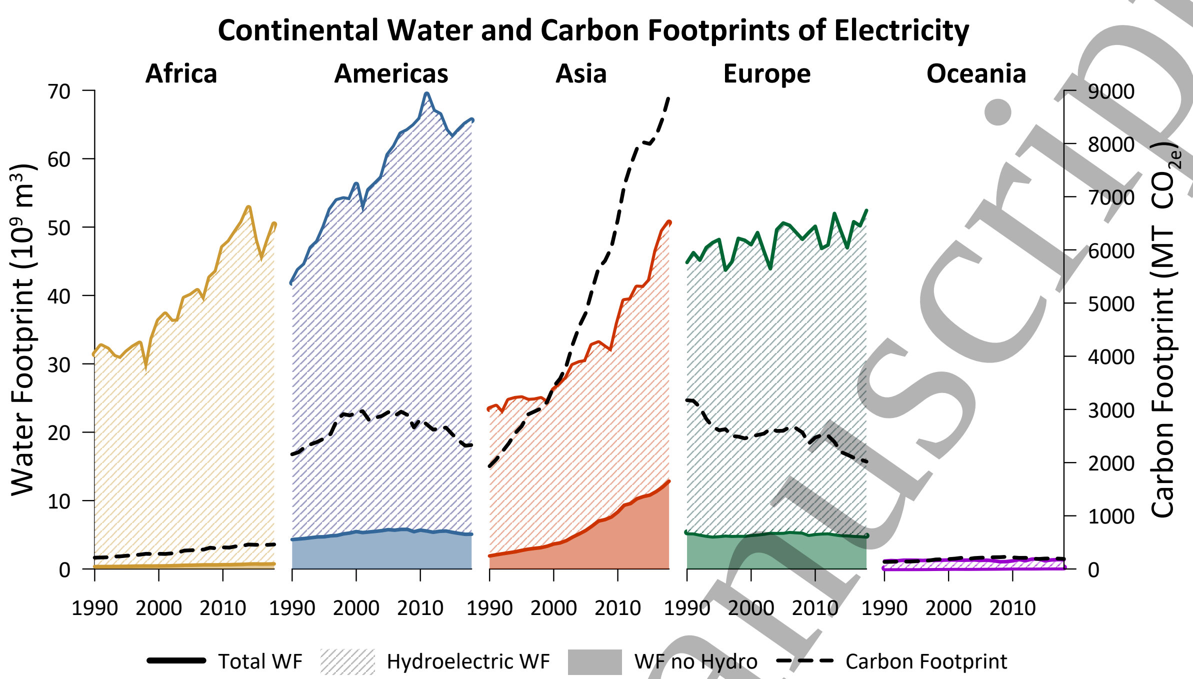

Figure 5. Continental scale water and carbon footprints of electricity from 1990 to 2018 show the coupled increase in carbon and water footprints in Africa and Asia. Total water footprints are shown with a solid line, where the area under the curve shows the separation of the hydroelectric (hatched) and non-hydroelectric (shaded) portions of the water footprint. The black dashed line shows the total carbon footprint.

Table 1. Per capita changes in water and carbon intensities of electricity generation in continental-scale regions.

	Water Footprint (1000 m^3/capita)			Carbon Footprint (kg CO_{2e}/capita)		
Continent	**1990**	**2004**	**2018**	**1990**	**2004**	**2018**
Africa	47	44	40	340	390	360
Americas	56	65	65	3000	3300	2300
Asia	7.0	7.7	11	600	1200	2000
Europe	62	68	70	4400	3600	2700
Oceania	41	40	33	4900	6200	4600

or country-specific empirical estimates. We are further limited by the availability of water use estimates for hydroelectricity, relying on a single global-scale analysis [8]. Additionally, water intensities used in this study are static in time, with a single water use factor applied over the study period. Therefore, changes in the electricity water footprint are the direct result of changes in a country's (or region's) shifting electricity profile. Given the lack of temporal and spatial estimates of global water consumption for electricity, this is a necessary assumption. In the case of thermal power plants, this is unlikely to cause a difference in the order of magnitude of our estimation, given the small relative range of water consumption intensities across fuels and cooling systems.

However, using one year of data to calculate water footprints for hydroelectricity introduces considerable uncertainty, given that water consumption in this case is influenced by local climatic conditions that are not captured here. We recognize the large variability in hydropower water footprints, globally [61]. To ameliorate this variability, site-specific estimates would be preferable to capture this limitation. For example, recent studies have investigated the water footprint of hydropower in Ecuador [62–64], Brazil [65], and the United States [10]. However, these studies are not available for all countries, have slight differences in methodologies, and a global inventory of these footprints is outside the scope of the current work. Therefore, we choose static water footprints with a consistent methodology [8].

Other considerations that could impact water and carbon footprints are the inclusion of traded electricity and the expansion of the footprint accounting method beyond the operational stage. Traded electricity across borders carries a water and carbon footprint that can affect the importing country's electric footprint. Previous studies have investigated this trade for embedded water and carbon footprints at the regional [66, 67], country [68–70], continental [71], and global scales [15, 72]. In 2018, the total traded virtual water footprint of electricity totaled 3.43 km^3 [15] compared to the total water footprint of 221 km^3 computed in this study (1.6%). Therefore, from a global perspective, the influence of this exclusion is relatively low. However, some countries, like Thailand that imports nearly 90% of their electricity, would be more impacted by this exclusion than others. Further, we focus exclusively on the operational footprints of electricity, ignoring the carbon and water impacts of fuel refinement or extraction. For fossil fuels like coal, the operational footprint dominates the total impact [35]. Biofuels, on the other hand, have a significant water footprint of production would would increase the total water footprint of electricity substantially [73]. We elect to exclude the footprints of production to maintain a consistent boundary on the analysis.

Despite these study limitations, our results provide useful, order of magnitude estimations of the global water and carbon footprint of electricity and illustrate overall trends. Additionally, the results provide important, long-term benchmarks for evaluation of global electricity generation.

5. Conclusions

Through this analysis, we show the last three decades of carbon and water footprints for electricity at the country, region, and continental scale. Examining the historic environmental trends for the electricity sector reveals that most countries are failing to reduce the carbon footprint of their electricity sector at a rate consistent with targets set in the Paris Agreement. Additionally, very few countries have been able to reduce the water impact of their electricity grids. In fact, based on reported electricity generation portfolios, carbon emissions for the electricity sector are increasing at a rate of 2.2% per year while water footprints of electricity are increasing at 1.6% per year. Because the electricity sector contributes to both global and local environmental degradation, we note the importance of examining these relationships at various spatial scales. At the regional scale, we see the tension between prioritising carbon reduction and the development of and access to electricity services. At the continental scale, we see the influence of cheap fossil fuel generation driving steep increases in carbon footprint in Asia and maintaining sizeable carbon and water footprints in Europe and the Americas. Additionally, per capita footprints of carbon and water of electricity are increasing in Asia, outpacing population growth.

The quantification of these trends in water footprints is important, considering projected impacts of climate change. While this study does not, specifically, discuss climate change impacts, many studies suggest an increased scarcity of water resources, globally [54]. A growth in water footprints associated with electricity removes available water for other uses, including irrigation and human consumption, in an already stressed environment. Water scarcity in the Mekong River basin results in an increase of carbon emissions due to reduced hydropower [34]. Additionally, the Mediterranean region of Europe is expected to experience decreased thermoelectric power generation efficiency due to water stress [58]. Evaluation of water and carbon footprint trends provide important benchmarks to evaluate future constraints under climate change-induced water scarcity.

As the global electricity sector continues to transition with the priority of decreasing our carbon intensity, we must also consider the water resource implications and limitations of these changes. Further, as we continue to trade electricity outside of country boundaries, the local water and carbon implications of generation are extended to geographically diffuse consumers [15, 71]. Therefore, decisions at the local and country-scale have global implications not just from carbon emissions, but also for sustainable water management.

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Author Contributions C.M.C. and R.A.M.P. formulated the study and wrote the manuscript. R.A.M.P. compiled the data and performed the analysis. C.M.C. and R.A.M.P. created figures and tables, and analyzed the results.

References

[1] Peter H Gleick. Water and energy. *Annual Review of Energy and the Environment*, 19(1):267–299, 1994.

[2] Karen Hussey, Jamie Pittock, et al. The energy-water nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society*, 17:31, 2012.

[3] Morgan Bazilian, Holger Rogner, Mark Howells, Sebastian Hermann, Douglas Arent, Dolf Gielen, Pasquale Steduto, Alexander Mueller, Paul Komor, Richard SJ

Tol, et al. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy pPolicy*, 39(12):7896–7906, 2011.

[4] Christopher M. Chini and Ashlynn S. Stillwell. Where are all the data? The case for a comprehensive water and wastewater utility database. *Journal of Water Resources Planning and Management*, 143(3):01816005, 2017. doi: 10.1061/(ASCE)WR.1943-5452.0000739.

[5] D Sesma-Martin and M Rubio-Varas. The weak data on the water-energy nexus in Spain. *Water Policy*, 2019.

[6] Morten Andreas Dahl Larsen, Stefan Petrovic, RE Engström, Martin Drews, S Liersch, Kenneth Bernard Karlsson, and M Howells. Challenges of data availability: Analysing the water-energy nexus in electricity generation. *Energy Strategy Reviews*, 26:100426, 2019.

[7] Kelly T Sanders. Critical review: Uncharted waters? the future of the electricity-water nexus. *Environmental Science & Technology*, 49(1):51–66, 2015. ISSN 0013-936X.

[8] Mesfin M Mekonnen, PW Gerbens-Leenes, and Arjen Y Hoekstra. The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research & Technology*, 1(3):285–297, 2015.

[9] Junguo Liu, Dandan Zhao, PW Gerbens-Leenes, and Dabo Guan. China's rising hydropower demand challenges water sector. *Scientific Reports*, 5(1):1–14, 2015.

[10] Emily A Grubert. Water consumption from hydroelectricity in the United States. *Advances in Water Resources*, 96:88–94, 2016.

[11] Tor Haakon Bakken, Ånund Killingtveit, and Knut Alfredsen. The water footprint of hydropower production—state of the art and methodological challenges. *Global Challenges*, 1(5):1600018, 2017.

[12] Lu Liu, Mohamad Hejazi, Hongyi Li, Barton Forman, and Xiao Zhang. Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nature Energy*, 2(17109):1, 2017.

[13] Christopher M. Chini, Lauren E. Excell, and Ashlynn S. Stillwell. A review of energy-for-water data in energy-water nexus publications. *Environmental Research Letters*, 15(12):123011, 2021.

[14] JC Zhang, R Zhong, P Zhao, HW Zhang, Y Wang, and GZ Mao. International energy trade impacts on water resource crises: an embodied water flows perspective. *Environmental Research Letters*, 11(7):074023, 2016.

[15] Rebecca A M Peer and Christopher M Chini. An integrated assessment of the global virtual water trade network of energy. *Environmental Research Letters*, 15 (11):114015, 2020.

[16] Anna Merce Rio Carrillo and Christoph Frei. Water: A key resource in energy production. *Energy Policy*, 37(11):4303–4312, 2009.

[17] Rebecca AM Peer and Kelly T Sanders. The water consequences of a transitioning US power sector. *Applied Energy*, 210:613–622, 2018.

[18] Mort Webster, Pearl Donohoo, and Bryan Palmintier. Water–CO2 trade-offs in electricity generation planning. *Nature Climate Change*, 3(12):1029–1032, 2013.

[19] Chao Zhang, Laura Diaz Anadon, Hongpin Mo, Zhongnan Zhao, and Zhu Liu. Water- carbon trade-off in China's coal power industry. *Environmental Science & Technology*, 48(19):11082–11089, 2014.

[20] Rebecca AM Peer, Jared B Garrison, Craig P Timms, and Kelly T Sanders. Spatially and temporally resolved analysis of environmental trade-offs in electricity generation. *Environmental Science & Technology*, 50(8):4537–4545, 2016.

[21] Md AB Siddik, Christopher Matthew Chini, and Landon Marston. Water and carbon footprints of electricity are sensitive to geographical attribution method. *Environmental Science & Technology*, 54(12):7533–7541, 2020.

[22] Li Liu, Zihua Yin, Peng Wang, Yiwei Gan, and Xiawei Liao. Water-carbon trade-off for inter-provincial electricity transmissions in China. *Journal of Environmental Management*, 268:110719, 2020.

[23] Ariel Miara, Jordan E Macknick, Charles J Vörösmarty, Vincent C Tidwell, Robin Newmark, and Balazs Fekete. Climate and water resource change impacts and adaptation potential for US power supply. *Nature Climate Change*, 7(11):793, 2017.

[24] Michelle TH Van Vliet, John R Yearsley, Fulco Ludwig, Stefan Vögele, Dennis P Lettenmaier, and Pavel Kabat. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, 2(9):676, 2012.

[25] Catherine E Raptis, Michelle TH van Vliet, and Stephan Pfister. Global thermal pollution of rivers from thermoelectric power plants. *Environmental Research Letters*, 11(10):104011, 2016.

[26] Ariel Miara, Charles J Vörösmarty, Jordan E Macknick, Vincent C Tidwell, Balazs Fekete, Fabio Corsi, and Robin Newmark. Thermal pollution impacts on rivers and power supply in the Mississippi River watershed. *Environmental Research Letters*, 13(3):034033, 2018.

[27] Lauren H Logan and Ashlynn S Stillwell. Probabilistic assessment of aquatic species risk from thermoelectric power plant effluent: Incorporating biology into the energy-water nexus. *Applied Energy*, 210:434–450, 2018.

[28] Lauren H Logan, Rohini S Gupta, Amy Ando, Cory Suski, and Ashlynn Stillwell. Quantifying tradeoffs between electricity generation and fish populations via population habitat duration curves. *Ecological Modelling*, 440:109373, 2021.

[29] Christopher M Chini, Lauren H Logan, and Ashlynn S Stillwell. Grey water footprints of US thermoelectric power plants from 2010–2016. *Advances in Water Resources*, 145:103733, 2020.

[30] Andrew J Kondash, Dalia Patino-Echeverri, and Avner Vengosh. Quantification of

the water-use reduction associated with the transition from coal to natural gas in the US electricity sector. *Environmental Research Letters*, 14(12):124028, 2019.

[31] Emily A Grubert, Fred C Beach, and Michael E Webber. Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal-and natural gas-fired electricity. *Environmental Research Letters*, 7(4):045801, 2012. ISSN 1748-9326.

[32] IA Grant Wilson and Iain Staffell. Rapid fuel switching from coal to natural gas through effective carbon pricing. *Nature Energy*, 3(5):365–372, 2018.

[33] AFM Kamal Chowdhury, Thanh Dang, Arijit Bagchi, and Stefano Galelli. Expected benefits of Laos' hydropower development curbed by hydro-climatic variability and limited transmission capacity–opportunities to reform. *Journal of Water Resources Planning and Management*, 146(10):05020019, 2020. doi: 10.1061/(ASCE)WR.1943-5452.0001279.

[34] AFM Kamal Chowdhury, Thanh Dang, Hung Tan Thai Nguyen, Rachel Koh, and Galelli Stefano. The Greater Mekong's climate-water-energy nexus: how ENSO-triggered regional droughts affect power supply and CO_2 emissions. *Earth's Future*, 2021.

[35] Measrainsey Meng, Emily Grubert, Rebecca AM Peer, and Kelly T Sanders. Spatially allocating life cycle water use for US coal-fired electricity across producers, generators, and consumers. *Energy Technology*, page 1901497, 2020.

[36] Jin Yang and Bin Chen. Energy–water nexus of wind power generation systems. *Applied Energy*, 169:1–13, 2016.

[37] Rebecca A M Peer and Christopher M Chini. Country-level water and carbon intensity estimates of electricity from 1990-2018, 2021. URL `https://doi.org/10.5281/zenodo.4560776`.

[38] International Energy Agency. Data and statistics, 2020. URL `https://www.iea.org/data-and-statistics`.

[39] U.S. Environmental Protection Agency. Emissions & generation resource integrated database (eGRID), 2018. URL `https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid`.

[40] Jordan Macknick, Robin Newmark, Garvin Heath, and KC Hallett. Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. *Environmental Research Letters*, 7(4):045802, 2012.

[41] E. S. Spang, W. R. Moomaw, K.S. Gallagher, P.H. Kirshen, and D.H. Marks. The water consumption of energy production: an international comparison. *Environmental Research Letters*, 9:105002, 2014.

[42] Rebecca AM Peer and Kelly T Sanders. Characterizing cooling water source and usage patterns across US thermoelectric power plants: a comprehensive assessment

of self-reported cooling water data. *Environmental Research Letters*, 11(12):124030, 2016.

[43] Evan G R Davies, Page Kyle, and James A Edmonds. An integrated assessment of global and regional water demands for electricity generation to 2095. *Adv. Water Resour.*, 52:296–313, February 2013.

[44] H S Eggleston, L Buendia, K Miwa, T Ngara, and K Tanabe. 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. Technical report, IPCC, 2006.

[45] International Energy Agency (IEA). CO2 emissions from fuel combustion: Database documentation (2020 edition). Technical report, International Energy Agency (IEA), 2020.

[46] United Nations. Standard country or area codes for statistical use (m49), 2020. URL `https://unstats.un.org/unsd/methodology/m49/`.

[47] Carey W King, Ashlynn S Stillwell, Kelly M Twomey, and Michael E Webber. Coherence between water and energy policies. *Nat. Resources J.*, 53:117, 2013.

[48] Glen P Peters, Robbie M Andrew, Josep G Canadell, Sabine Fuss, Robert B Jackson, Jan Ivar Korsbakken, Corinne Le Quéré, and Nebojsa Nakicenovic. Key indicators to track current progress and future ambition of the paris agreement. *Nature Climate Change*, 7(2):118–122, 2017.

[49] David L McCollum, Wenji Zhou, Christoph Bertram, Harmen-Sytze De Boer, Valentina Bosetti, Sebastian Busch, Jacques Després, Laurent Drouet, Johannes Emmerling, Marianne Fay, et al. Energy investment needs for fulfilling the Paris Agreement and achieving the sustainable development goals. *Nature Energy*, 3(7): 589–599, 2018.

[50] Genovaitė Liobikienė and Mindaugas Butkus. The European Union possibilities to achieve targets of Europe 2020 and Paris Agreement climate policy. *Renewable Energy*, 106:298–309, 2017.

[51] Emily Grubert. Fossil electricity retirement deadlines for a just transition. *Science*, 370(6521):1171–1173, December 2020.

[52] European Union. EU climate target plan 2030: Building a modern, sustainable and resilient Europe, 2020. URL `https://ec.europa.eu/clima/policies/eu-climate-action`.

[53] Lauri Myllyvirta. China's new 20130 targets promise more low-carbon power than meets the eye. *Carbon Brief*, 2020. URL `https://www.carbonbrief.org/analysis-chinas-new-2030-targets-promise-more-low-carbon-power-than-meets-the-eye`.

[54] Mesfin M Mekonnen and Arjen Y Hoekstra. Four billion people facing severe water scarcity. *Science Advances*, 2(2):e1500323, 2016.

[55] Paolo D'Odorico, Kyle Frankel Davis, Lorenzo Rosa, Joel A Carr, Davide Chiarelli, Jampel Dell'Angelo, Jessica Gephart, Graham K MacDonald, David A Seekell,

Samir Suweis, et al. The global food-energy-water nexus. *Reviews of Geophysics*, 56(3):456–531, 2018.

[56] Arjen Y Hoekstra and Mesfin M Mekonnen. The water footprint of humanity. *Proceedings of the National Academy of Sciences*, 109(9):3232–3237, 2012.

[57] Guy Ziv, Eric Baran, So Nam, Ignacio Rodríguez-Iturbe, and Simon A Levin. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences*, 109(15):5609–5614, 2012.

[58] PA Behrens, Michelle TH van Vliet, T Walsh B Nanninga, Rodriques JF Dias, et al. Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nature*, 2:17114, 2017.

[59] United Nations. World population prospects 2019, 2021. URL https://population.un.org/wpp/Download/Standard/Population/.

[60] World Bank. World development indicators, 2020. URL https://databank.worldbank.org/reports.aspx?source=world-development-indicators.

[61] Laura Scherer and Stephan Pfister. Global water footprint assessment of hydropower. *Renewable Energy*, 99:711–720, 2016.

[62] S Vaca-Jiménez, PW Gerbens-Leenes, and S Nonhebel. Water-electricity nexus in Ecuador: The dynamics of the electricity's blue water footprint. *Science of The Total Environment*, 696:133959, 2019.

[63] S Vaca-Jiménez, PW Gerbens-Leenes, and Sanderine Nonhebel. The water footprint of electricity in Ecuador: Technology and fuel variation indicate pathways towards water-efficient electricity mixes. *Water Resources and Industry*, 22:100112, 2019.

[64] S Vaca-Jiménez, PW Gerbens-Leenes, and Sanderine Nonhebel. The monthly dynamics of blue water footprints and electricity generation of four types of hydropower plants in Ecuador. *Science of the Total Environment*, 713:136579, 2020.

[65] Clívia Dias Coelho, Demetrius David da Silva, Gilberto Chohaku Sediyama, Michel Castro Moreira, Silvio Bueno Pereira, and Ângela Maria Quintão Lana. Comparison of the water footprint of two hydropower plants in the Tocantins River Basin of Brazil. *Journal of Cleaner Production*, 153:164–175, 2017.

[66] Benjamin L Ruddell, Elizabeth A Adams, Richard Rushforth, and Vincent C Tidwell. Embedded resource accounting for coupled natural-human systems: An application to water resource impacts of the western us electrical energy trade. *Water Resources Research*, 50(10):7957–7972, 2014.

[67] Richard R. Rushforth and Benjamin L. Ruddell. The vulnerability and resilience of a city's water footprint: The case of Flagstaff, Arizona, USA. *Water Resources Research*, 2016. ISSN 1944-7973. doi: 10.1002/2015WR018006. URL http://dx.doi.org/10.1002/2015WR018006.

582 [68] Evan Kodra, Seth Sheldon, Ryan Dolen, and Ory Zik. The North American electric grid as an exchange network: An approach for evaluating energy resource composition and greenhouse gas mitigation. *Environmental Science & Technology*, 49(22):13692–13698, 2015.

586 [69] Christopher M Chini, Lucas A Djehdian, William N Lubega, and Ashlynn S Stillwell. Virtual water transfers of the US electric grid. *Nature Energy*, 3(12): 1115, 2018.

589 [70] Lucas A Djehdian, Christopher M Chini, Landon Marston, Megan Konar, and Ashlynn S Stillwell. Exposure of urban food–energy–water (FEW) systems to water scarcity. *Sustainable Cities and Society*, 50:101621, 2019.

592 [71] Christopher M Chini and Ashlynn S Stillwell. The changing virtual water trade network of the European electric grid. *Applied Energy*, 260:114151, 2020.

594 [72] Christopher M Chini and Rebecca AM Peer. The traded water footprint of global energy from 2010 to 2018. *Scientific Data*, 8(1):1–8, 2021.

596 [73] Mesfin M. Mekonnen, P.W. Gerbens-Leenes, and Arjen Y. Hoekstra. Future electricity: The challenge of reducing both carbon and water footprint. *Science of The Total Environment*, 569–570:1282 – 1288, 2016. ISSN 0048-9697. doi: http://dx.doi.org/10.1016/j.scitotenv.2016.06.204. URL `http://www.sciencedirect.com/science/article/pii/S0048969716313936`.